Eur. Phys. J. A **2**, 227–231 (1998)

THE EUROPEAN PHYSICAL JOURNAL A
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Short note

Fusion around the barrier in ^{11,9}Be + ^{209}Bi

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Received: 2 April 1998
Communicated by B. Povh

Abstract. The ^{9}Be + ^{209}Bi fusion cross sections were measured in the range 37.5 MeV $\leq E_{lab} \leq$ 45.0 MeV at the Munich Tandem via the observation of ground state α-decay of the evaporation residues. Fusion cross sections of ^{209}Bi with the "halo" ^{11}Be unstable projectile in the region around the Coulomb barrier were deduced from an experiment done with the same technique at the RIKEN Ring Cyclotron. Above the Coulomb barrier the ^{11}Be cross sections are larger than the ^{9}Be ones in agreement with theoretical predictions based on the larger ^{11}Be halo radius. Also below the barrier these theories foresee the same behavior in disagreement with the experimental results, since the two cross sections are rather similar.

PACS. 25.70.Jj Fusion and fusion-fission reactions

Measurements of fusion cross sections induced by halo nuclei around the Coulomb barrier are presently important to understand whether the interactions involving such nuclei show different signs from the interactions between stable nuclei or not.

Extended theoretical work has already been done on this topic, in particular for the "best system" ^{11}Li + ^{208}Pb [1–5], with contradictory predictions. In fact if one considers only the influence of the halo structure, which means a r.m.s. matter radius larger than the usual value deduced by the $r_o \times A^{1/3}$ systematics, the subbarrier fusion cross section is enhanced since the Coulomb barrier is lowered; however, if one considers also the very low binding energy of the last nucleon(s), intimately related to the halo structure, and the breakup cross section, expected to be quite large, the sub-barrier fusion cross section could be even more enhanced [3, 4] or hindered according to how these two facts are handled.

From the experimental view point real challenges have to be faced due to the fact that halo unstable beams are produced by secondary reactions with intensities several order of magnitude smaller than the stable ones, with modest emittance and with low energy resolution.

The present work is focused on the measurement and the comparison of the fusion cross sections of the two systems ^{11,9}Be + ^{209}Bi around the Coulomb barrier; the ^{11}Be nucleus has a very well established neutron halo structure. This research is connected to the work of [6] which studies the influence of the breakup process on the fusion in the systems ^{9,10,11}Be + ^{209}Bi immediately above the Coulomb barrier.

Very few investigations have been done up to now in this field. The systems ^{11,9}Be + ^{238}U were studied with considerable effort at GANIL [7], but the statistics collected did not allow significant conclusions. The systems ^{27,29,31}Al + ^{197}Au are under study at RIKEN [8].

The aim of this work was to find whether the fusion cross section of the unstable nucleus ^{11}Be with ^{209}Bi is larger than that induced by the stable ^{9}Be nucleus on ^{209}Bi particularly at energies immediately below the Coulomb barrier. The ^{11}Be matter radius [9, 10] is 2.73 $\pm$ 0.05 fm, $\sim$ 10% higher than the value obtained from $r_o \times A^{1/3}$ systematics, and consequently the Coulomb barrier is about 1 MeV lower; for these reasons the fusion

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cross section should be enhanced if breakup effects are in first approximation neglected.

The work was developed according to two parallel lines. The ^{9}Be + ^{209}Bi fusion cross section was measured in the energy range 37.5 MeV $\leq E_{lab} \leq$ 45.0 MeV with high accuracy at the Tanden Van de Graaff accelerator of the Munich Universities. The previous experiment [6] on this system was focused on the 3n and 4n channels above the Coulomb barrier, and only few points below the barrier were measured with low energy resolution due to a rather thick target ($\sim$ 600 μg/cm^2). The data for the system ^{11}Be + ^{209}Bi were obtained from the experiment of [6] at the RIKEN Ring Cyclotron analyzing in smaller steps the ^{11}Be beam energies. In this case the main effort was directed to measure cross sections down to $\sim$ 10 mb because of statistics originated by the low intensity of the ^{11}Be radioactive beam. In both experiments the cross sections were deduced by the in beam yield of the α-particles emitted from the ground state decay of the evaporation residues produced in the fusion-evaporation reaction.

In the ^{9}Be + ^{209}Bi experiment the target was natural Bismuth 220 μg/cm^2 thick evaporated onto a 150 μg/cm^2 Carbon foil; backing thickness was chosen to stop at the target site the recoiling evaporation residues. Four silicon detectors were installed in a $\sim$ 60 cm diameter scattering chamber. Two detectors, 100 μm thick, with an effective surface of around 415 mm^2, positioned at +135^o (-160^o), $\sim$ 7 (10) cm from the target, were used for the detection of the α particles emitted by the evaporation residues; two monitor detectors, $\sim$ 300 μm thick, with an active surface of 12.6 mm^2, were positioned at $\pm$ 20.0^o at a distance of $\sim$ 25 cm. The incoming beam was well collimated by means of 3 mm diameter diaphragm followed by two 4 mm diameter antiscattering collimators located 20 to 10 cm from the target. The beam intensity was kept between 2 to 10 enA, and the used charge state was 4$^+$. The signals of the four detectors were processed by the same acquisition system so that no dead time correction was necessary. The absolute cross sections were calculated from the known Rutherford cross sections deduced from the monitor detectors spectra and from the solid angle ratios between the monitors and the α detectors. Two monitor were utilized to make precise corrections for small changes in the beam direction. The solid angle ratios were evaluated from the detectors geometry and experimentally measured using the intensity of the α particles emitted by ^{211}At, $T_{1/2}$ = 7.22 h, E_α = 5.867 MeV and ^{211}Po, E_α = 7.450 MeV β^+ daughter of ^{211}At with $T_{1/2}$ = 0.52 s and consequently appearing also with $T_{1/2}$ = 7.22 h. These activities were produced in beam, at the target position by the decay of ^{215}Fr populated by 3n emission channel.

The overall accuracy of the measured cross section is better than 5% except for the two lowest energy points whose accuracy is anyhow better than 10%.

The following α-channels were observed: 4n, ^{214}Fr, E_α = 8.477, 8.547 MeV, $T_{1/2}$ = 5.0 ms g.s.decay and E_α = 8.426 MeV, $T_{1/2}$ = 3.35 ms decay of the E_x = 0.123 MeV metastable level; 3n, ^{215}Fr, E_α = 9.360 MeV, $T_{1/2}$ = 90 ns; 2n, ^{216}Fr, E_α = 9.005 MeV, $T_{1/2}$ = 700 ns; p3n, ^{214}Rn, E_α = 9.037 MeV, $T_{1/2}$ = 270 ns. The last two channels as well as the 4n ones emit α-particles too close in energy to be resolved. Excitation functions were measured in the energy range 37.5 MeV $\leq E_{lab} \leq$ 45.0 MeV in 0.5 to 1.0 MeV steps. Fig. 1a shows some typical α energy spectra.

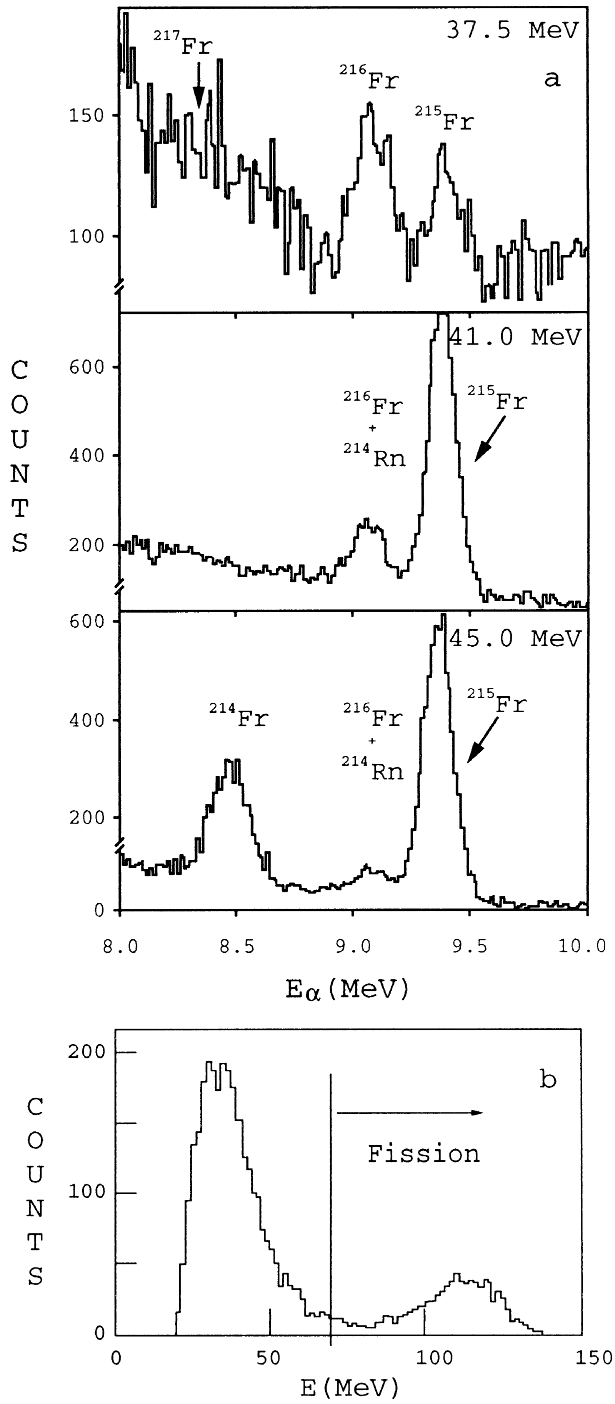

Fig. 1. a In beam α-spectra from the reaction ^{9}Be + ^{209}Bi detected at lowest, intermediate and highest laboratory beam energies. The arrow in the top panel indicates the expected position of the 1n channel, ^{217}Fr, E_α = 8.315 MeV, not observed and not expected according to CASCADE calculations. **b** Total fission events in the reaction ^{11}Be + ^{209}Bi

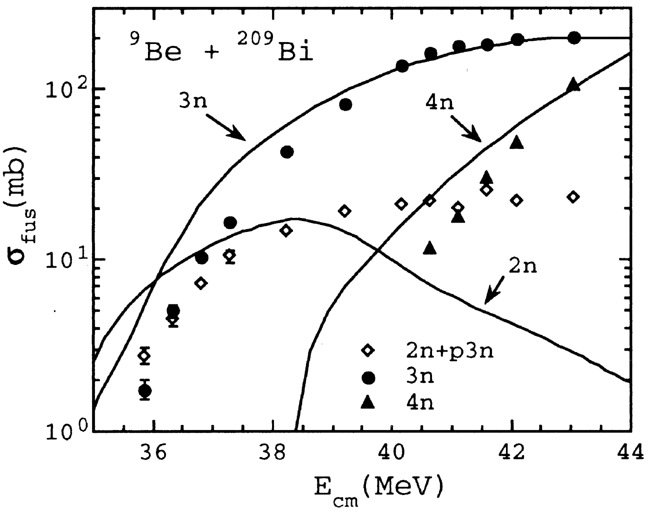

Fig. 2. Excitation functions of the evaporation channels observed in the $^9Be + ^{209}Bi$ fusion reaction. Continuous lines give the results of CASCADE evaporation code; p3n channel is not reported since the calculation always gives $\sigma \leq 0.1$ mb

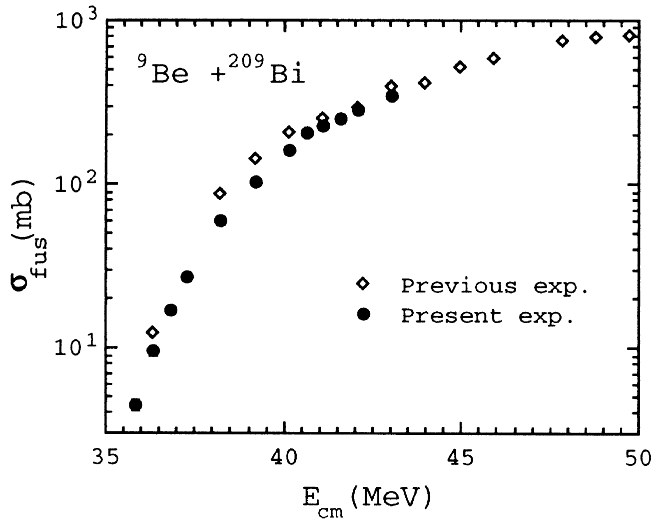

Fig. 3. Experimental total fusion cross sections for the system $^9Be + ^{209}Bi$ compared with previous data [6]; errors are smaller than symbols

The excitation functions for all the observed channels are presented in Fig. 2 together with the estimates of the evaporation code CASCADE taken from [6]. Total fusion cross sections were calculated adding all the observed channels, shown in Fig. 2, and the fission one extracted from Ref. 6 data. Calculations with the CASCADE code confirm that in this energy range only the considered channels add up to the fusion cross section. In Fig. 3 data are compared with the total cross sections of previous work [6] where the contribution from the mixed 2n and p3n channels, not reported there, was taken from the interpolation of present data. We believe that discrepancies between the two sets of data might be attributed to normalization errors in data of [6] where only one monitor detector was used. Anyhow, for the present work the weighted average of the two data sets was adopted.

The cross sections for the system $^{11}Be + ^{209}Bi$ were obtained from a more detailed analysis of the data collected in the previous experiment [6]. The ^{11}Be beam had a continuous energy distribution due to the method adopted for its production. The excitation function was obtained by recording event by event the time of flight of the ^{11}Be ions; then the continuous TOF distribution was cut in 2 ns bins, corresponding to $\sim$ 3.7 MeV energy intervals, in order to get adequate statistics for the relative comparison of the 4n and 5n exit channels. By a careful inspection of the data, since the timing resolution was estimated better than 0.3 ns, it was concluded that a new analysis of the data in 1 ns bins, corresponding to $\sim$ 1.8 MeV energy intervals, was possible and worthwhile in order to get more energy points at cost of statistics. This was the only way to get for the first time significant data with halo nuclei in the important region below the barrier. Fission cross sections were also obtained. Events with E $\geq$ 70 MeV in the large area Si detectors spectra, were assigned as fission events as shown in Fig. 1b; this assignment was confirmed by coincidence data between each of the four pairs of Si detectors symmetrically located around 90^o (details of pertinent experimental set-up are reported in [6]).

New 1 ns bins data and old 2 ns bins results are in agreement above $E_{cm} = 40$ MeV, where the cross sections are $\geq$ 100 mb. Below 40 MeV, where we get from the new analysis two points and only one from the old one ($\sim$ 15 mb at 37.5 MeV), the new cross sections are higher than the old ones beyond the statistical error; this is due to uncertanties of the peak definition originated by the low statistics. As a consequence the conclusions related to the lowest cross section point have to be considered as tentative.

Total fusion cross sections were obtained as the sum of the 4n, 5n, and the fission channels; the result is shown in Fig. 4 and compared with $^9Be + ^{209}Bi$ one. The ^{11}Be data are corrected for the energy loss in the four targets, which had a total thickness of $\sim$ 4mg/cm^2, and for the steep rising of the cross sections. This is quite relevant for the subbarrier fusion since the effective energy is shifted of about +1 MeV. A similar correction was applied for the ^9Be case, but it is much less relevant since in that case the target was only 220 μg/cm^2 thick.

From the comparison between the ^9Be and the ^{11}Be fusion cross sections two points have to be underlined:
i) above the barrier the ^{11}Be cross sections are systematically higher than the ^9Be ones, ii) below the barrier the two cross sections are rather similar. The low energy behavior is unexpected since ^{11}Be, due to the halo, has a considerable larger radius, which lowers the Coulomb barrier, and consequently a cross section larger than that obtained with ^9Be is expected. Based on the same arguments, a similar effect is expected above the barrier as indeed observed.

In order to understand this behavior simple fusion cross section calculations, where only the halo structure was taken into account, were done. This halo structure, which implies a 10% difference between the nuclear radii, is indeed the most significant difference between ^{11}Be and ^{9}Be. Theoreticians have pointed out in many papers the relevance of the loseness of the last bound neutron in addition to the halo; the expected breakup process and/or a possible hypothetical soft dipole resonance, still under discussion, could effect the subbarrier fusion cross section. But in the present case in addition to ^{11}Be with $S_n = 0.503$ MeV also ^{9}Be with $S_n = 1.67$ MeV is rather weakly bound, consequently the breakup phenomena could have similar effects on both systems and in any case the accuracy of ^{11}Be data does not allow to enlight this point.

Two sets of calculations were done. The first with the standard CCFUS code. In the case of ^{11}Be a slight modification of the original code was done in order to include the larger radius (Δr = +0.24 fm with respect to the $1.18\times A^{1/3}$ systematics), the corresponding new barrier height V_b and new width $\hbar\omega$. Coupling to higher Be states were not included since below the neutron threshold ^{11}Be with $1/2^+$ g.s. has only one excited state at 0.32 MeV, $1/2^-$, which can be excited only via E1 transition and the ^{9}Be first excited state at 1.68 MeV is already unbound. For the spherical target nucleus ^{209}Bi with $9/2^-$ g.s. the couplings to the first two excited levels at 0.9 MeV, $7/2^-$, B(E2) = 0.44(7) W.u., and at 1.6 MeV, $13/2^-$, B(E3) = 7(6) W.u. [11], were included; anyhow these two couplings have very small effect. The results are shown in Fig. 4.

In order to take into account in a more proper way the halo mass distribution, a second set of calculations (theory 2) more sophisticated and potentially more accurate was done. A more realistic potential was evaluated folding both target and projectile nucleon distributions (double folding model) with the M3Y nucleon nucleon interaction. Experimental density distributions were utilized for ^{11}Be [10,12] and ^{9}Be, ^{209}Bi [13]. From this potential barrier height, curvature and radius were extracted and utilized in the classical Wong formulas to get the fusion cross sections. A check done at some energies with the more elaborate coupled channel code ECIS [14] with this potential and following the same approach, gave the same results. The calculated curves are shown in Fig. 4.

Both sets of calculations, in particular the ones based on M3Y interaction, foresee for ^{11}Be subbarrier fusion cross sections considerably larger than for ^{9}Be in contradiction with experimental data. The difference between the two calculations gives an indication of the present limitations of the theoretical description of the process. The behavior above the barrier is well reproduced by both theories; this clearly originates from the ^{11}Be larger haloradius. Therefore within these approximations there is no theoretical explanation of all the experimental results but only of the data above the barrier.

The inclusion of breakup effects in the calculations seems not to be able to better reproduce the experimental data. In fact, within the approach of [4], where calculations were done for the combination ^{11}Li + ^{208}Pb, very similar to ^{11}Be + ^{209}Bi, the inclusion of the breakup should increase the difference between the ^{11}Be ($S_n = 0.503$ MeV) and ^{9}Be ($S_n = 1.67$ MeV) predicted cross sections. Moreover, preliminary calculations [15] done for the present system with [4] code, which includes the breakup, need abnormal and unrealistic breakup strength in order to reproduce both ^{11}Be and ^{9}Be data. The alternative approach of the Brazilian group [1, 2] foresee, on the contrary, a lowering of the cross sections due to the loss of strength because of breakup itself. This should lower the ^{11}Be cross sections more than the ^{9}Be ones and bring the two theoretical cross sections closer, but this would make the discrepancies between the measured and predicted cross sections for ^{9}Be even bigger.

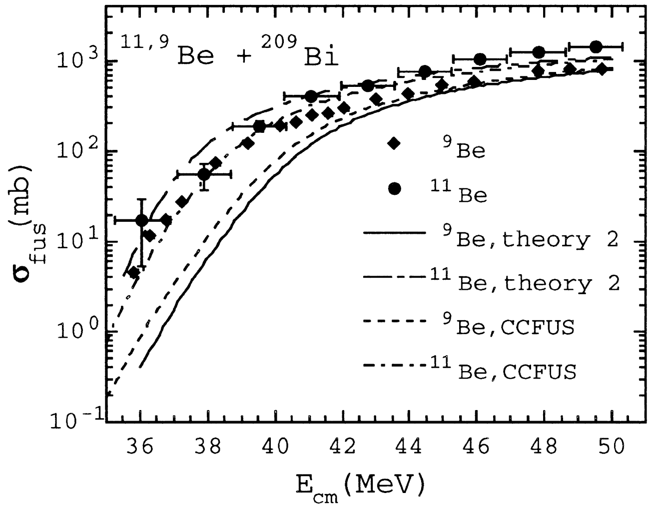

Fig. 4. Total fusion cross sections for ^{11,9}Be + ^{209}Bi compared with the results of CCFUS code and fusion calculations based on Wong formulas with the inclusion of the potential calculated with the M3Y nucleon nucleon interaction (theory 2)

A last point to be noted is that ^{9}Be subbarrier cross sections are underestimated in both calculations. One possible origin of this might be that standard nuclear potential adopted in the codes is not adequate for nuclei like ^{9}Be much less bound than most of the stable nuclei. Since the potential diffuseness is closely related to the nucleon separation energy, in loosely bound nuclei such potential might have a larger effective radius, the barrier might be lower, and consequently the cross section becomes larger. This point needs to be further investigated because other effects (transfer, breakup,...) could be considered to recover this underestimation.

In summary, for the first time we have measured, using the unstable ^{11}Be beam, fusion cross sections for the ^{11}Be +^{209}Bi and have compared them with those obtained for the ^{9}Be + ^{209}Bi system. In the subbarrier region the relative behavior, within the large errors for the ^{11}Be data, is unexpected since the two cross sections do not differ so much, while simple theoretical calculations predict for ^{11}Be considerably larger cross sections than for ^{9}Be. The behavior above the barrier, i.e. ^{11}Be fusion cross sections larger than for ^{9}Be, is well explained by the theory. Therefore for the moment there is no clear explanation of all the experimental results.

This first investigation suggests also that a more accurate measurement of the subbarrier fusion cross sections with ^{11}Be should be considered since this experiment was done with a beam intensity of $\sim 10^{+5}$ part/s. Unfortunately the ^{11}Be beam seems to be not an easy one for the Radioactive Beam Facilities under construction like SPIRAL, Oak Ridge, EXCYT, REX-ISOLDE.

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